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Effects of UV-C treatment on inactivation of *Salmonella enterica* and *Escherichia coli* O157:H7 on grape tomato surface and stem scars, microbial loads, and quality☆

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ABSTRACT

The purpose of this study was to investigate the effectiveness of ultraviolet-C (UV-C) light inactivation as affected by the location of pathogens on the surface and at stem scars of whole grape tomatoes. A mixed bacterial cocktail containing a three strain mixture of *Escherichia coli* O157:H7 (C9490, E02128 and F00475) and a three serotype mixture of *Salmonella enterica* (*S.* Montevideo G4639, *S.* Newport H1275, and *S.* Stanley H0558) were used. Tomatoes were spot inoculated using approximately 100 μL of inocula to achieve a population of about $10^{7\pm1}$ CFU/tomato. Additionally, the effects of treatment on color, texture, lycopene content, and background microbial loads during post UV-C storage at 4 °C for 21 days were determined. Results showed that UV-C doses of 0.60–6.0 kJ/m^2 resulted in 2.3–3.5 log CFU per fruit reduction of *E. coli* O157:H7 compared to 2.15–3.1 log CFU per fruit reduction for *Salmonella* on the surfaces. Under the same conditions, log reductions achieved at stem scar were 1.7–3.2 logs CFU for *E. coli* O157:H7 and 1.9–2.8 logs CFU for *Salmonella*. The treatment was effective in controlling native microbial loads during storage at 4 °C as the total aerobic mesophilic organisms (PCA) and anaerobic lactic acid bacteria (LAB) counts of treated tomatoes were significantly ($p < 0.05$) lower during storage compared to the control group and the yeast and mold populations were reduced significantly below the detection limit. Furthermore, the firmness of tomato and its color was not affected by the UV-C doses during storage. UV-C radiation could potentially be used for sanitizing fresh tomatoes and extending shelf-life. The results of this study indicate that the specific location of pathogens on the produce influences the effectiveness of UV-C treatment, which should be taken into consideration for the design of UV-C systems for produce sanitization.

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1. Introduction

Investigation into human nutrition indicates that a diet rich in fruits and vegetables can provide a protective role against the development and progression of cardiovascular diseases; this evidence supports dietary guidelines encouraging fruit and vegetable consumption (Ignarro, Balestrieri, & Napoli, 2007; Liu et al., 2000). Consequently, consumption of fresh vegetable and fruit increased by 19% from 1970 to 2005 (Wells & Buzby, 2008) and is predicted to continue to increase through 2020 (Lin et al., 2003). Tomatoes are of particular interest and used extensively because of their health promoting components such as carotene, lycopene, and phenolic compounds (Beecher, 1998; Sahlin, Savage, & Lister, 2004). Unfortunately, with the increase in produce consumption, the number of produce-related outbreaks of foodborne illnesses also increased (Lynch, Tauxe, & Hedberg, 2009), and the microbial safety of produce remains a serious public-health concern in developed countries. From 1998 to 2007, fresh produce caused almost 23% of all foodborne illness (CSPI, 2009). About 58% of the

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contaminating microbial species are of zoonotic origin (Franz & van Bruggen, 2008), including *Escherichia coli* O157:H7, *Salmonella* and *Listeria monocytogenes*. Approximately 1990 human culture-confirmed cases of salmonellosis that occurred during 1990–2007 were traced to various types of tomatoes including roma and grape (Bidol et al., 2007). The serovars of *Salmonella* that were associated with these outbreaks included Braenderup, Montevideo, Newport, Typhimurium, Baildon, Litchfield, Mbandaka, Muenchen, Poona, Senftenberg, Javiana and others (Bidol et al., 2007; Jackson, Griffin, Cole, Walsh, & Chai, 2013).

Contamination of tomatoes with pathogens can occur anywhere along the preharvest to postharvest continuum. Once contaminated, *Salmonella* can survive and grow throughout the normal shelf life period of tomato (Beuchat & Mann, 2008) and can internalize in spite of low tissue pH (ca. 4) of the fruit (Asplund & Nurmi, 1995); and can potentially multiply to a population of about 7 logs under appropriate environment (Weissinger, Chantarapanont, & Beuchat, 2000). To prevent tomato-associated outbreaks, a wide range of chemical sanitizers has been investigated with varying degrees of success (Beuchat, 1998; Lang, Harris, & Beuchat, 2004). Chlorine containing or peracetic acid based sanitizers are most widely used as a postharvest treatment (Artés & Allende, 2005; Pao, Kelsey, & Long, 2009). Chlorine wash was reported to be somewhat effective in inactivating pathogens and spoilage microorganisms by 1–2 log cycles (Brackett, 1999) and even with intensive treatment (320 ppm chlorine for 2 min) complete inactivation of *Salmonella* Montevideo on tomato surfaces was not achieved (Zhuang, Beuchat, & Angulo, 1995). Moreover, chlorine reacts with the organic load and is capable of forming harmful toxic compounds such as chloroform, chloramines and trihalomethanes (Richardson et al., 1998) which may cause new regulatory restrictions (Allende, Aguayo, & Artes, 2004; Artes, Gomez, Aguayo, Escalona, & Artes-Hernundez, 2009) due to its residual toxicity and impact on produce quality and human health. Thus, it is of interest to develop an effective alternative strategy to chlorine-based sanitizers wash.

Non-ionizing irradiation using ultraviolet light (UV-C), wavelengths 200–280 nm, with 90% emission at 253.7 nm, has long established applications in food surface decontamination due to its antimicrobial capacity (US-FDA, 2002). The germicidal effect of UV light is due to the interruption of bacterial replication and the formation of thymine dimers in the bacterial chromosome (Giese & Darby, 2000). Yaun, Sumner, Eifert, and Marcy (2004) reported 2.2 logs reduction of *Salmonella* spp. on tomato surfaces by UV-C light at a dose of 25 mJ/cm^2. Besides the germicidal activity, UV-C light is capable of inducing positive physiological responses by stimulating defense mechanisms in treated produce. UV-C treatment as a postharvest treatment has proven effective in controlling rot development, delaying decay and senescence in tomatoes (Liu et al., 1993), carrots (Mercier & Arul, 1993), grapes (Nigro, Ippolito, & Lima, 1998) and in other produce. UV-C treatment efficacy depends on the spatial arrangement between the UV-C source and the produce and also on the treatment dose and since UV-C treatment is a surface sterilization method, the effectiveness also depends on the actual location of the pathogens on the produce surface, surface composition, surface topography and transmissivity (Allende, McEvoy, Luo, Artés, & Wang, 2006; Gardner & Shama, 2000). Although there are reports on UV-C treatment of tomatoes for inactivation of pathogens (Sommers, Sites, & Musgrove, 2010; Yaun et al., 2004), none of these studies examined the effects of UV-C on microbial inactivation in key surface active sites such as 'stem scar' which preferentially harbor microorganisms. Also, there are no reported data on the effect of UV-C treatment on spoilage bacteria population and quality of grape tomatoes during storage.

Previously we reported on inactivation of pathogens on tomato using an integrated treatment of UV-C light with low dose gamma irradiation (Mukhopadhyay, Ukuku, Fan, & Juneja, 2013). The purpose of the present study was to evaluate the effectiveness of different doses of UV-C radiation alone to inactivate foodborne pathogens including *Salmonella enterica* and *E. coli* O157:H7 located on the surface and stem scar sites of tomato. The other objective was to examine the treatment efficacy to control the growth of native microflora responsible for spoilage and the effect of UV-C on sensory quality and color of tomato during storage.

2. Material and methods

2.1. Grape tomatoes (Solanum lycopersicum)

Whole Grape tomatoes, fresh and unblemished, were purchased (from the same lot) from a local retail store (Wyndmoor, PA). The tomatoes were purchased on the day before the experiment and were stored at 4 °C without any washing or any sanitizing.

2.2. Strain, growth conditions, and inoculums preparation

A bacterial cocktail composed of three strain of *E. coli* O157:H7 (C9490, E02128 and F00475) and three serotypes of *S.* enterica (*S.* Montevideo G4639, *S.* Newport H1275, and *S.* Stanley H0558) were used for this work. Selection of these strains was based on their association, mainly with produce related outbreaks. *E. coli* O157:H7 (E02128) was associated with a lettuce outbreak and *E. coli* O157:H7 (F00475) was isolated from a spinach outbreak in 2006 (Uhlich, Sinclair, Warren, Chmielecki, & Fratamico, 2008), while *E. coli* O157:H7 (C9490) was isolated from an uncooked hamburger outbreak that occurred in the 1990s (CDC, 1993). These isolates were obtained from in-house (USDA-ARS-ERRC) culture collection. *S.* Montevideo G4639, which was isolated from a tomato-associated outbreak, was received from Dr. Larry Beuchat at the University of Georgia. *S.* Newport H1275 and *S.* Stanley H0558 both were associated with alfalfa sprout-related outbreaks and were obtained from Dr. Patricia Griffin, Center for Disease Control and Prevention, Atlanta, GA. The bacterial strains were grown by two successive loop transfers of individual strains incubated at 37 °C for 24 h in 5 ml Tryptic Soy Broth (TSB, BBL, BD Difco, Sparks, MD). A final transfer of 0.2 ml was made into 50 ml TSB with incubation at 37 °C for 18 h. The bacterial cells were harvested by centrifugation (5000 × *g*, 15 min) at 4 °C. Cell pellets were washed twice in 0.1% (w/v) peptone water (PW, BBL, BD Difco) and was finally suspended in PW to an achieve target level of 8–9 log CFU/ml. To enumerate the population densities in each cell suspension, appropriate dilutions (in 0.1% PW) were spiral plated (model D, Spiral Biotech, Bethesda, MD), in duplicate, on to tryptic soy agar (TSA; BD Difco) plates. Equal volumes of each culture were combined in a separate sterile test tube to obtain a cocktail of three strains of *Salmonella* and *E. coli* O157:H7 (8–9 log CFU/ml) prior to inoculation of tomato.

2.3. Inoculation of grape tomato

A spot inoculation method was used to inoculate tomatoes since it allows the application of a known amount of cells onto the surfaces, regardless of weight/size. Hundred microliter (100 μl, ca. 10 drops) of the mixed culture suspension was carefully spotted on the stem scar (ST) and surface (SR) sites of tomatoes using an appropriate accurate pipette. To assure optimum exposure to UV-C radiation, intended inoculation sites of tomato were marked with indelible ink. The inoculated tomatoes were placed on sterile Petri dishes and air-dried for 2 h at room temperature (22 °C) in a biosafety cabinet (Nuare™, Plymouth, MN, USA) to allow the

bacteria to attach to the surfaces of tomatoes and to minimize the growth of cells during drying. Following inoculation and cell attachment, tomatoes were subjected to UV-C radiation as described below.

2.4. UV-C treatment of inoculated tomatoes

Inoculated Grape tomatoes were treated with UV-C radiation by placing the inoculated surface under an ultraviolet light source generated by eight germicidal low-pressure mercury-vapor fluorescent lamps (model FG15T8, 15 W, Buylighting.com, Burnsville, MN) mounted into a casing (Ultra-Violet Products, San Gabriel, CA). The lamps emitted about 90% of their irradiation at 254 nm covering 1200 cm^2 cross sectional area. UV-C intensity was determined prior to treatment by measuring the light intensity (mW/cm^2/s) using a UVX digital radiometer (UVP Inc., Upland, CA). The applied dose (mJ/cm^2) was calculated by multiplying the emitting UV light intensity with treatment time in seconds. Light intensity was evaluated several times during the experiments to ensure consistent output. Tomatoes were exposed to UV-C light with inoculated area (surface, SR or stem scar, SC) facing the UV-C lamp for duration of 0–100 s. The calculated UV-C dose after radiation was 0, 0.6, 1.2, 2.4, 3.6, 4.8, and 6.0 kJ m^{-2}, respectively. All UV-C radiation experiments were carried out at room temperature (ca. 22 °C) and relative humidity of about 60%, unless otherwise stated.

2.5. Bacterial enumeration

For determination of the number of surviving pathogenic bacteria in control (inoculated but untreated) and inoculated treated sample, sterile water was combined with each sample in 1:2 ratio (wt:vol.) and pummeled in stomacher bags with a Stomacher 400 laboratory blender (Seward, Worthington, UK) for 2 min at 230 rpm to obtain a slurry. Decimal serial dilutions of the suspensions were then prepared in 0.1% PW. Surviving bacterial populations on tomato surfaces were evaluated by plating 0.1 ml on nonselective tryptic soy agar medium (TSA, BBL, Difco, Sparks, MD). After 5 h, TSA plates were overlaid with an appropriate selective medium for each bacteria; Sorbitol MacConkey (SMAC, BD Difco) agar for *E. coli* O157:H7, Xylose-lysine-tergitol 4 (XLT-4, BBL, BD Difco) for *S. enterica*. Experiments were conducted in triplicate. The plates were incubated for 24 h at 37 °C and the colonies were counted and expressed as log CFU/tomato.

2.6. Background microbial load

Whole grape tomatoes were enumerated for indigenous microflora counts study. The untreated (controls) tomatoes and the tomatoes treated with UV-C were packaged separately in a plastic container (ClearPAC®, Dart Container Corp., Mason, MI, USA) with a lid perforated with 4 holes (0.6 mm dia.). The packaged tomatoes were then stored at 5 °C for over 3 weeks. At 0, 7, 14 and 21 days, samples were withdrawn from storage for microbiological analyses. For each determination, five (5) tomatoes, weighing approximately 60 ± 1 g, were placed in a Stomacher® bag with 150 ml of 0.1% PW and pummeled for 30 s in Stomacher (model 400, Dynatech Laboratories, Alexandria, VA, USA) set at 230 rpm. Decimal dilutions of the samples were made with 0.1% PW, and aliquots (0.1 ml) were spread plated in duplicate on to a range of media. Plate Count Agar (PCA, BD Difco) with incubation at 30 °C for 48 h was used for enumeration of mesophilic aerobic bacteria. Dichloran Rose Bengal Chlortetracycline (DRBC, BD Difco) agar with incubation at 25 °C for 5 days was used for enumeration of yeast and mold. For lactic acid bacteria (LAB), deMan Rogosa Sharpe agar (MRS; BD Difco) was used and the plates were incubated at 35 °C for 3–5 days (Flowers, Hall, & Ledenbach, 2001). DRBC plates were wrapped with aluminum foil. Experiments were conducted independently 3 times ($n = 3$). Colonies were counted and reported as log CFU/g of tomato.

Table 1
E. coli O157:H7 and *Salmonella enterica* population reduction on surface and stem scars of tomatoes after different doses of UV-C treatment.

Dose (kJ m^{-2})	*E. coli* O157:H7 population reduction (log CFU $tomato^{-1}$)		*Salmonella enterica* population reduction (log CFU $tomato^{-1}$)	
	Surface	Stem scar	Surface	Stem scar
0.6	2.25 ± 0.11 Da	1.60 ± 0.10 Eb	2.15 ± 0.23 Da	1.93 ± 0.11 Da
1.2	2.70 ± 0.08 Ca	2.27 ± 0.09 Db	2.33 ± 0.16 CDa	2.16 ± 0.08 CDa
2.4	3.05 ± 0.16 Ba	2.59 ± 0.10 Cb	2.57 ± 0.03 BCa	2.37 ± 0.09 BCa
3.6	3.29 ± 0.10 ABa	2.83 ± 0.12 BCb	2.75 ± 0.11 ABa	2.56 ± 0.11 ABa
4.8	3.44 ± 0.22 Aa	3.04 ± 0.08 ABb	2.90 ± 0.25 ABa	2.67 ± 0.07 ABa
6.0	3.49 ± 0.21 Aa	3.17 ± 0.07 Ab	3.06 ± 0.39 Aa	2.81 ± 0.06 Aa

Initial counts of *Salmonella enterica* and *E. coli* O157:H7 were 7.6 ± 0.20 and 8.0 ± 0.14 log CFU (mean ± standard deviation) per tomato fruit, respectively.
Data followed by different upper case letters in the same column are significantly ($p < 0.05$) different.
Data followed by different lower case letters in the same row are significantly ($p < 0.05$) different.

2.7. Color analysis

The color of tomatoes was measured at 1, 7, 14 and 21 d of storage. Color (CIE L*, a*, b*) was measured with a Hunter lab Miniscan XE colorimeter (Hunter Associates Laboratory, Reston, VA, U.S.A.). The color meter instrument was calibrated using the standard white and black plates. The Hunter Lab values (L*, a* and b*) of tomato samples were obtained at randomly selected spots on the tomato surface and were monitored throughout the display storage period. Two readings were taken on the surface of each tomato. Six tomatoes for each replicate were measured, and there were a total of 24 measurements for each treatment per experiment.

2.8. Texture evaluation

The texture of the samples was measured using a Texture Analyser (Model XT2i; Stable Micro Systems, England). The analysis employed was the return-to-start (RTS) method, measuring force under compression with a 6 mm cylindrical probe (P6), recording the peak of maximum force. Whole tomato was axially compressed to 75% of its original height for penetration probes. Force–time curves were recorded at a speed 1 mm/s for cylindrical probes. The results were expressed in maximum grams.

2.9. Statistical analyses

All experiments were done in triplicate with duplicate samples enumerated at each sampling time. Data were analyzed by SAS (version 9.2) statistical package (SAS Institute Inc., Cary, NC.) for analysis of variance (ANOVA) and the Bonferroni LSD method (Miller, 1981, pp. 67–70) to estimate significant differences ($p < 0.05$) between mean values of number of cells recovered after each treatment.

3. Results and discussion

3.1. Inactivation of S. enterica and E. coli O157:H7 inoculated on tomatoes with UV-C dosages

The effects of different UV-C dose treatments on inactivation of *S. enterica* and *E. coli* O157:H7 on whole grape tomatoes, located on

the surface and at stem scar, at 22 °C are presented in Table 1. The recovered initial population (mean value) of *S. enterica* and *E. coli* O157:H7 from tomato were approximately 7.6 ± 0.2 and 8.0 ± 0.14 log CFU per tomato fruit, respectively. The population of *Salmonella* and *E. coli* O157:H7 decreased with increasing UV-C dose. As UV dose increased from 0 to 0.6 kJ m^{-2} (10 s exposure), there was a rapid decrease in surviving pathogen populations (mean value) from the initial level (dose 0 kJ m^{-2}) of 7.6 ± 0.20 to 5.5 ± 0.2 log (surface) and 5.7 ± 0.3 log (stem scar) for *Salmonella* and from the initial level (dose 0 kJ m^{-2}) of 8.0 ± 0.14 to 5.8 ± 0.1 log (surface) and 6.4 ± 0.3 log (stem scar) for *E. coli* O157:H7, respectively. The population of pathogens continued to decrease with further increase in UV-C dose, but at a much slower rate (Table 1).

Table 1 also provides a comparison of log reductions of pathogens on the surface and at stem scar of tomato achieved at various doses. UV-C doses 0.6–6.0 kJ m^{-2} resulted 2.25–3.5 log reductions for *E. coli* O157:H7 on the surface compared to 2.15–3.1 log reduction for *Salmonella*. Under the same condition, the log reduction achieved at stem scar was 1.65–3.2 logs for *E. coli* O157:H7 and 1.9–2.8 logs for *Salmonella*. At 0.6 kJ/m^2 UV-C, approximately 2.25 and 2.15 log CFU reductions were achieved for *E. coli* O157:H7 and *S. enterica,* respectively, on tomato surface, indicating about 5% ($p > 0.05$) greater resistance for *Salmonella* spp. compared to *E. coli* O157:H7. In fact, the resistance of *S. enterica*, on tomato surface or stem scar, to UV-C treatment was higher compared to *E. coli* O157:H7 at all treatment doses (0.6–6.0 kJ/m^{-2}).

All doses of UV-C reduced the population of pathogens inoculated on tomatoes. However, the log reduction was significantly ($p < 0.05$) influenced by low doses of 0.6–2.4 kJ m^{-2}. There is a clear trend that higher doses of UV-C lead to greater reductions of *E. coli* O157:H7 and *S. enterica* on tomato. Although the log reduction continued to increase with treatment intensity, no significant dose differences observed at higher doses (>2.4 kJ m^{-2}). This is probably due to the fact that UV-C light inactivates microorganisms by preventing DNA replication and the damage at cellular level starts with the initial dose. As dose exceeds cellular injury threshold, rapid lethal destruction of cells occurs. The inactivation process continues with additional dose increment, but cellular death begins to level off (Sastry, Datta, & Worobo, 2000). Yaun et al. (2004) reported 2.19 log CFU/tomato reduction for *Salmonella* spp. on the tomato surface using UV-C dose of 0.24 kJ/m^2 while Sommers et al. (2010) obtained 2.6–3.1 logs CFU/g inactivation of *Salmonella* spp., *L. monocytogenes* and *Staphylococcus aureus* on the surface of Roma tomatoes with a UV-C dose of 5 kJ/m^2. The authors were unable to find any study on UV-C inactivation of common foodborne pathogens on whole grape tomato stem scar and consequently no report on comparison of pathogen inactivation on surface compared to stem scar site are available. In the present work, comparison of log reductions of *E. coli* O157:H7 and *Salmonella* spp. on surface and at stem scar presented interesting findings (Table 1). Result indicated lower log reductions at the stem scars compared to surface of tomato for both *S. enterica* and *E. coli* O157:H7 due to UV-C inactivation. However, the difference in log reduction for *E. coli* O157:H7 between stem scar and surface was twice as high as the difference in log reduction for *Salmonella*. Moreover, it is interesting to note that unlike *Salmonella* spp., log reduction values between the stem scar and surface for *E. coli* O157:H7 were all significantly ($p < 0.05$) different (Table 1). This is indicative of higher resistance of the pathogens to UV-C radiation at the stem scar. The lack of dose response at the stem scar compared to smooth surface may be due to the difference in surface topography which is known to substantially affect the surface energy and bulk properties of a material. The stem scar site is uneven and rough and hence might have provided stronger bonding or attachments for pathogens compared to those located on smooth surface site. In addition, the uneven nature of stem scar surface might have partially shielded the organisms from UV-C radiation, which is a non-penetrating form of electromagnetic radiation. Yaun et al. (2004) reported a higher log reduction (ca. 3.3 logs) when UV-C (24 mJ/cm^2) was applied to smooth apple surface inoculated with *E. coli* and lower log reductions were obtained for uneven leafy lettuce surface inoculated with *Salmonella* spp. (2.65 logs) and *E. coli* O157:H7 (2.79 logs). In assessing the validity of use UV-C radiation for inactivation of various foodborne pathogens (*L. monocytogenes*, *Salmonella* spp. and *S. aureus*), Sommers et al. (2010) also reported higher (>10 fold) log reduction for pathogens on a smooth stainless steel surface compared to rough textured raw meat and poultry. Wei et al. (1995) reported that an inoculated *Salmonella* population on the tomato surface died after 5 day while the population at the stem scars was resistant and survived, even after washing with 100 ppm of aqueous chlorine for up to 2 min. Stem scar locations were reported to provide protective environments for *Salmonella* during controlled atmosphere and passive modified atmosphere packaging. The *Salmonella* Enteritidis population was actually increased by 1 log at stem scars of cherry tomatoes during 10 days storage while cells on the surface died completely (Das, Gurakan, & Bayındırlı, 2006). However, Schmidt, Palekar, Maxim, and Castilo (2006) observed lower surviving populations of *Salmonella* on tomato stem scars (4.7 logs) compared to cubes (5.0–5.4 logs) while investigating the effect of electron beam irradiation on *Salmonella* in fresh-cut tomatoes. This is in contrast to the current finding where pathogens on the surface were sensitive compared to pathogens located at stem scars. This disagreement is probably due to the difference in inactivation techniques used and the state of food substrate. In present work, intact whole fruit was exposed to UV-C dose, compared to previous work where tomato was cut into cubes and stem scars sections before experiment. It is possible that the available nutrients from cut tomatoes flesh could have encourage renewed survivability for pathogens present in the cubes and hence higher number survivors compared stem scars.

UV-C treatment for tomato was effective against test pathogens compared to other methods of treatments at their specific concentrations. Water or active antimicrobial washing is a common postharvest practice in the produce industry to minimize the microbial contamination. A water wash was capable of removing 1–2 logs of *S.* Enteritidis, *L. monocytogenes* and *E. coli* O157:H7 on tomatoes (Venkitanarayanan, Lin, Bailey, & Doyle, 2002). Effectiveness of chlorinated water, which is the most common antimicrobial sanitizer used in the produce industry, is reported to depend on the chlorine concentration, contact time, pathogen type, and its location on the produce. Reduction in inoculated *Salmonella* spp. was 1.0 log for 40 s washing with 200 ppm free chlorine (Weissinger et al., 2000) and 3–4 logs for 40 min washing (Beuchat, Harris, Ward, & Kajs, 2001). For inoculated *E. coli* O157:H7 on tomato surfaces treated with 200 ppm free chlorine for 3 min, reduction was 1.5 log (Beuchat, Nail, Adler, & Clavero, 1998). Although antimicrobial washes are proven to be effective to some extent in killing the pathogens on the surface of produce, they are ineffective for internalized pathogens. Chlorine wash at 200 ppm failed to eliminate *E. coli* O157:H7 when internalized in lettuce tissue and other vegetables (Niemira, 2008; Nthenge, Weese, Carter, Wei, & Huang, 2007). Other potential sanitizers such as ozonated water, organic acids, hydrogen peroxide, and phosphates have been investigated but none was capable of inactivation of bacterial populations above 2 logs (Beuchat et al., 1998). Sapers and Jones (2006) reported 1.4 log CFU/g reductions for inoculated *Salmonella* and *E. coli* population on tomato with 1% H_2O_2 at 20 °C for

20 min treatment, whereas 5% H_2O_2 at 60 °C reduced the population of these pathogens by 2.6 log CFU/g. Popular surfactants like sodium lauryl sulfate, sodium dodecyl sulfate and Tween 80, produced similar log reductions for *Salmonella* on tomato surface as with simple water wash and therefore, were considered as ineffective in removing pathogens from tomato surface (Raiden, Sumner, Eifert, & Pierson, 2003).

Pathogen contamination can occur in the field during postharvest processing, anywhere on the produce (Ryser, Yan, & Hao, 2009). In this study, the potential use of UV-C light as a decontamination strategy for foodborne pathogens such as *E. coli* O157:H7 and *S. enterica* on fresh tomato surface and stem scar has been demonstrated. Ultraviolet light is a U.S. Food and Drug Administration approved nonthermal intervention technology that can be used for decontamination of food surfaces. Pathogen inactivation data on stem scar should be included when developing UV-C based method for produce.

3.2. Effect of UV-C treatment on the microbial loads of grape tomatoes during storage

One of the major concerns for the produce industry is limited shelf life. Several studies have indicated that significant improvement of shelf life for fruits and vegetables can be achieved by ultraviolet light treatment due to inactivation of spoilage organisms and delayed ripening process (Arvanitoyannis, Stratakos, & Tsarouhas, 2009). Due to its delicate tissue structure, tomatoes are very susceptible to injury and microbial invasion. The bacterial populations and factors that influence their growth play an important role in the postharvest quality of produce (Soler-Rivas, Jolivet, Arpin, Olivier, & Wichers, 1999).

The influence of UV-C dose treatment on the aerobic mesophilic bacteria (PCA), anaerobic LAB, and yeast and mold (DRBC) population on whole tomatoes was evaluated over the entire duration of storage at 5 °C for 21 days. Change in the mean total aerobic mesophilic microorganism populations of the control and UV-C treated tomatoes are shown in Table 2. The initial PCA count of control sample was 4.6 ± 0.4 logs CFU g^{-1}. This is in agreement with reported (Prakash, Manley, DeCosta, Caporaso, & Foley, 2002) total aerobic microorganism population on untreated tomato of 4.4 logs CFU/g. Lower test doses (0.6–1.2 kJ/m^2) had very little or no effect on the initial populations of aerobic mesophilic bacteria, whereas higher test doses (4.8–6.0 kJ/m^2) produced reasonable (0.45–0.65 logs) but not significant ($p > 0.05$) population reduction. At a dose of 6.0 kJ/m^2, the initial population reduced from 4.57 logs to 3.92 logs, (Table 2). In general, the initial microbial load was reduced by about 0.03–0.65 log CFU g^{-1} by UV-C treatment. However, PCA counts increased in all treatment groups during first 14 days of storage before falling on day 21. The control samples showed the highest PCA count (5.98 log CFU g^{-1}) on day 14 compared to UV treated samples (5.41–5.95 log CFU g^{-1}). Although, the PCA counts decreased with increasing UV-C dose there was no significant statistical ($p > 0.05$) difference among the UV-C treatments.

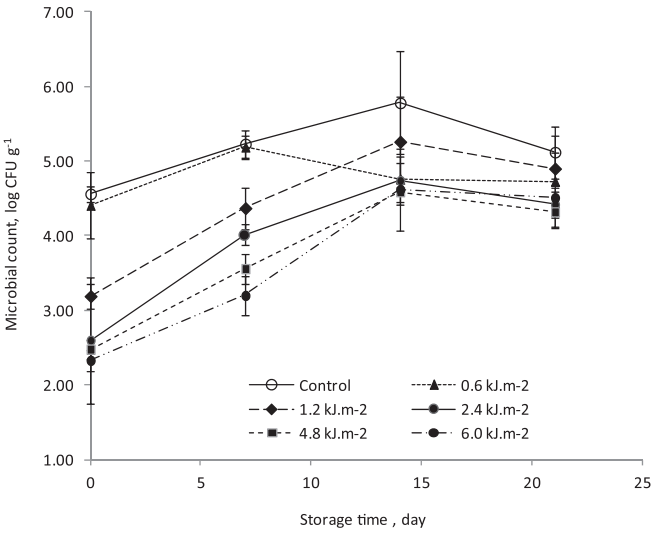

Fig. 1. Effect of UV-C dose on MRS plate counts (LAB) of tomato stored for 21 day at 5 °C. Error bars represent standard deviation ($n = 3$).

Anaerobic Lactic acid bacteria (LAB) can cause spoilage of a variety of foods including fresh produce. The LAB count for both fresh control and UV-C treated tomatoes increased during first 2 weeks storage as shown in Fig. 1. After 2 weeks, LAB counts exhibited a declining trend, although, the final population reached higher (4.32–5.12 log CFU g^{-1}; $p > 0.05$) values compared to respective initial populations (2.33–4.56 log CFU g^{-1}). It is worth noting that except for 0.6 kJ/m^2 dose treatment, the initial LAB population (4.56 log CFU g^{-1}) of tomato was significantly ($p < 0.05$) reduced (3.19–2.33 log CFU g^{-1}) due to the UV-C treatment.

The effectiveness of UV-C treatment on yeast and mold population for the control and treated Grape tomatoes during storage for 21 day at 5 °C is given in Table 3. Initial total mold and yeast count on untreated control tomatoes was about 4.0 ± 0.2 log CFU/g. Earlier work by Schmidt et al. (2006) reported the presence of 1.6 and 2.3 log CFU/g molds and yeasts, respectively, for untreated Roma tomato cubes. This is in line with our finding although some variation is expected due to difference in the tomato type, cultivar, sample preparation and microbial recovery technique. The initial population of yeast and mold was reduced by 0.17–0.66 log CFU/g ($p > 0.05$) due to treatment with UV-C doses 0.6–2.4 kJ/m^2. However, the population reduced significantly ($p < 0.05$) from 3.96 logs to 2.00 logs and 1.95 logs due to treatment with 4.8 and 6.0 kJ/m^2 respectively, as shown in Table 3.

Postharvest rotting and spoilage occurs mainly due to molds and yeasts (Wang et al., 2008).

Microbial counts that influence changes in quality and rejection of minimally-processed produce are usually high (7–8 log CFU/g)

Table 2
Changes in the mean total aerobic mesophilic bacterial population, PCA (log CFU g^{-1}) of Control and UV-C treated tomatoes during storage at 5 °C for 21 days.

Storage time, day	Control	UV-C treated, dose, kJ/m^2				
		0.6	1.2	2.4	4.8	6.0
0	4.57 ± 0.39a^{B}	4.54 ± 0.37a^{B}	4.40 ± 0.62a^{C}	4.10 ± 0.59a^{B}	4.12 ± 0.60a^{B}	3.92 ± 0.24a^{C}
7	6.07 ± 0.63a^{A}	5.76 ± 0.50ab^{A}	5.55 ± 0.50ab^{AB}	5.27 ± 0.72ab^{A}	5.33 ± 0.66ab^{A}	5.08 ± 0.62b^{AB}
14	5.98 ± 0.60a^{A}	5.95 ± 0.64a^{A}	5.90 ± 0.73a^{A}	5.68 ± 0.67a^{A}	5.41 ± 0.54a^{A}	5.45 ± 0.49a^{A}
21	4.78 ± 0.19a^{B}	4.15 ± 0.21a^{B}	4.65 ± 1.48a^{BC}	4.10 ± 0.85a^{B}	4.15 ± 1.20a^{B}	4.13 ± 0.23a^{BC}

Mean values with different uppercase letters in same column are significantly different ($p < 0.05$).
Mean values with different lowercase letters in same row are significantly different ($p < 0.05$).

Table 3
Effect of UV-C dose on mold and yeast population (log CFU g^{-1}) of control and treated grape tomatoes during storage for 21 days at 5 °C.

Storage time, day	Control	UV-C treated, kJ/m^2				
		0.6	1.2	2.4	4.8	6.0
0	3.96 ± 0.17a^{A}	3.79 ± 0.50a^{A}	3.37 ± 0.70a^{A}	3.30 ± 0.99a^{A}	2.00 ± 0.52b^{A}	1.95 ± 0.23b^{A}
7	3.22 ± 0.31a^{AB}	3.02 ± 0.03ab^{B}	2.95 ± 0.49ab^{A}	2.48 ± 0.33ab^{B}	2.30 ± 0.52b^{A}	1.55 ± 0.20c^{A}
14	3.07 ± 0.32a^{B}	2.30 ± 0.18b^{B}	ND	ND	ND	ND
21	3.71 ± 0.20a^{AB}	2.74 ± 0.44b^{B}	ND	ND	ND	ND

ND = no detectable survivors.
Mean values with different uppercase letters in same column are significantly different ($p < 0.05$).
Mean values with different lowercase letters in same row are significantly different ($p < 0.05$).

(Ragaert, Devlieghere, & Debevere, 2007). The average shelf life of fresh fruits and vegetables are typically10–14 days (Cantwell & Suslow, 2002). Control of spoilage microorganisms can play an important role in the improvement of quality of produce like tomato. In the present work, the background microbial load (PCA plate count) for untreated tomatoes increased gradually from 4.6 logs to 4.8 logs over 21 days storage. For treated tomatoes, populations initially increased during first two weeks of storage before falling below 4.6 logs on day 21, except that for treatment with 1.2 kJ/m^2 (Table 2), when the final population reached to 4.65 logs on day 21.

The final LAB count of treated tomatoes were significantly ($p < 0.05$) lower after three weeks of storage due to UV-C treatments as compared to the control (Fig. 1). Also, for the treated tomatoes, the yeast and mold populations gradually decreased for all dose treatment groups and, as a matter of fact, the mold and yeast populations were reduced significantly to below the limit of detection ($<2.0 \times 10^1$ CFU/g) after 2 weeks of storage for all treatment groups except that for 0.6 kJ/m^2 (Table 3). Results demonstrate that UV-C dose treatments may be used to control background microbial growth.

Reports on the effect of UV-C doses on background microbial load of uncut whole fresh tomato are limited. Howard, Miller, and Wagner (1995) reported a reduction of aerobic mesophilic microflora of chopped tomato that had been irradiated with 1 kGy. Schmidt et al. (2006) observed a reduction of 1.3 logs lactic acid bacteria and greater than 3.9 logs mold and yeasts populations on ripe Roma tomato cubes after irradiation with 0.7 kGy electron beam. Prakash et al. (2002) reported no growth of aerobic background microflora and 2 logs reduction for the mold population through 12 days of storage for diced Roma tomatoes treated with 3.7 kGy Gamma irradiation. However, these reports used Gamma irradiation which is not viewed by the consumer groups as a popular method of preservation. The present work uses UV-C treatment which is widely accepted by consumer and is approved by the FDA as a food surface decontamination technique.

3.3. Effect of UV-C treatment on quality of grape tomato during storage

The firmness of tomato was not affected by the UV-C doses during post treatment storage (Table 4), except on day 1, when 4.8 kJ/m^2 treated tomato required significantly less force compared to tomato treated with 0.6 kJ/m^2, and on day 14, when tomato treated with 6.0 kJ/m^2 required significantly more force than 1.2 kJ/m^2 treated tomato. Firmness was influenced by storage time at doses 0.6 and 4.8 kJ/m^2, when fruits after 21-day storage required significantly less force compared to day 7 fruits. Over the duration of storage (day 0–day 21), the firmness of control fruit (820 ± 76 g) was reduced (not significantly).

As given in Table 4, UV-C treatment did not affect tomato color consistently. Color was expressed in terms of L*, a* and b* values, where L* value indicated luminosity (level of light or darkness); a* indicated chromaticity on a green (negative number) to red (positive number), and b* value indicated chromaticity on a blue (negative number) to yellow (positive number), respectively. The L* values of the treated fruits were significantly lower than the nontreated control (34.9 ± 0.68) after 3 weeks of storage. Lower L* values are indicative of darkening of tomato surface for the UV-C treated fruits after 21 days of storage. No significant changes in luminosity were observed during first two weeks of storage. The a* values were also decreased significantly compared to control (22.8 ± 2.05) after 21 days of storage indicating decreasing redness for the treated fruits. However, during first two weeks, the redness did not change significantly. Treated tomato always had higher b* values (not always significantly) compared to untreated controls, except for the treatment dose of 0.6 kJ/m^2 when the b* values were significantly higher. Higher b* values are indicative of the fact that UV treated tomatoes were slightly more yellowish than the nontreated controls. No consistent changes in the color parameter were observed during storage. The visual difference in color and appearance were not noticeable among the UV-C treated fruits during storage due the redness of tomato. In addition to inactivation of the microbial load, UV-C doses can cause cell damage and respiratory stress in produce (Escalona, Aguayo, Martínez-Hernández, & Artés, 2010). It is possible that UV-C light caused slight damage to the surface tissue of tomato immediately after treatment. The slight changes in color parameters, L*, a* and b*, are likely due to this minor damage of tomato surface tissues by UV-C.

4. Conclusions

In this study, the potential of a practical and relatively low dose UV-C radiation treatment for post harvest processing of tomatoes with minimal impact on the quality attributes has been demonstrated. All UV-C doses reduced the population of pathogens on tomatoes. However, the log reduction was significantly ($p < 0.05$) influenced by low doses (0.6–2.4 kJ m^{-2}). UV-C radiation of 0.6–6.0 kJ m^{-2} resulted in 2.3–3.5 logs reduction of *E. coli* O157:H7 and 2.1–3.1 logs reduction of *S. enterica* that was surface inoculated. Results indicate that the produce surface characteristics, e.g. smooth skin surface or rough stem scar surface, greatly influence the efficacy of the treatment. Log reductions were lower (10–17%) when pathogens were located at the stem scar site which is generally rough compared to smooth surface site. Higher roughness of stem scar surfaces may have promoted greater adhesion and shielding of pathogens from UV-C radiation and hence the higher resistance of pathogens located in stem scar. In contradiction to present work, Schmidt et al. (2006) observed higher surviving *Salmonella* population on fresh cut tomato cubes compared to stem scars when irradiated with electron beam. Differences in inactivation techniques and the state of food substrate are likely the cause for this

Table 4
Changes in texture and color parameters of tomatoes during storage as affected by UV-C light.

Treatment dose, KJ/m^2	Day 1	Day 7	Day 14	Day 21
Maximum force, *g*				
0	780 ± 46 Ax	744 ± 51 Ax	848 ± 48 Ax	730 ± 41 Ax
0.6	810 ± 74 Ax	715 ± 29 Ax	694 ± 64 BCxy	582 ± 64 By
1.2	783 ± 79 ABxy	811 ± 48 Ax	670 ± 57 Cy	696 ± 78 ABxy
2.4	793 ± 60 ABx	763 ± 65 Axy	740 ± 78 ABCxy	665 ± 71 ABy
4.8	688 ± 99 Byz	817 ± 16 Ax	789 ± 95 ABCxy	651 ± 82 ABz
6.0	702 ± 90 ABx	820 ± 25 Ax	801 ± 51 ABx	703 ± 87 ABx
L*				
0	33.3 ± 0.52 Ax	33.7 ± 1.12 Ax	32.7 ± 1.26 Ax	33.6 ± 0.78 Ax
0.6	33.2 ± 0.52 ABxy	34.8 ± 0.89 Ax	33.9 ± 1.26 Axy	32.4 ± 0.12 Ay
1.2	34.5 ± 0.63 Ax	33.9 ± 0.34 Ax	33.1 ± 1.61 Ax	32.7 ± 1.10 Ay
2.4	32.7 ± 0.60 By	34.6 ± 1.23 Ax	33.3 ± 0.92 Axy	32.8 ± 0.93 Ay
4.8	33.7 ± 1.21 ABx	34.1 ± 0.34 Ax	32.7 ± 1.24 Ax	32.1 ± 1.30 Ay
6.0	33.1 ± 0.90 ABx	33.2 ± 0.39 Ax	32.4 ± 1.15 Ax	32.3 ± 0.47 Ay
a*				
0	21.5 ± 1.28 ABx	20.2 ± 0.95 Bx	21.1 ± 1.02 Ax	17.6 ± 1.78 By
0.6	18.4 ± 1.28 By	20.9 ± 1.40 Bx	19.9 ± 2.12 Axy	18.6 ± 2.03 By
1.2	20.9 ± 1.63 Ay	23.4 ± 2.00 Ax	20.0 ± 1.31 Ay	18.2 ± 1.21 Ay
2.4	21.4 ± 1.24 Ax	18.8 ± 1.26 Byz	19.8 ± 1.53 Axy	17.3 ± 2.39 Bz
4.8	22.7 ± 0.93 Ax	19.7 ± 1.82 By	20.9 ± 1.62 Axy	19.1 ± 1.61 Ay
6.0	22.5 ± 1.12 Ax	20.1 ± 1.49 By	20.0 ± 1.22 Ay	18.5 ± 1.59 Ay
b*				
0	17.2 ± 0.53 Ax	18.5 ± 1.89 Bx	17.4 ± 0.85 Ax	17.1 ± 0.78 Bx
0.6	18.6 ± 1.26 Ay	19.4 ± 1.60 Ay	18.5 ± 1.84 Ay	18.1 ± 1.07 ABy
1.2	17.5 ± 1.13 Ax	17.7 ± 1.55 Bx	18.6 ± 1.21 Ax	18.1 ± 1.22 Ax
2.4	16.2 ± 0.84 Ax	16.6 ± 1.25 Bx	17.8 ± 1.36 Ax	16.9 ± 1.39 Bx
4.8	17.1 ± 0.91 Ax	18.3 ± 1.89 Bx	17.4 ± 1.67 Ax	16.1 ± 1.62 Bx
6.0	16.2 ± 0.92 Ax	16.5 ± 1.46 Bx	18.1 ± 1.43 Ax	16.5 ± 1.39 Bx

L*, a*, b* and texture were 34.9 ± 0.68, 22.8 ± 2.05, 16.1 ± 1.99, and 820 ± 76 g, respectively, on the day (day 0) of treatment.
The data represent means ± standard deviations ($n = 3$). Means with the same letter in the same column (A, B and C) and the same row (x, y and z) are not significantly different ($p > 0.05$).

disagreement. The available nutrients from fresh cut tomatoes flesh could have encourage renewed cell survivability for pathogens present in the cubes. Log reduction values between stem scar and surface for *E. coli* O157:H7 were significantly ($p < 0.05$) different but that was not true for *Salmonella* spp.

Results demonstrate that UV-C dose treatments can be used to control background microbial growth. The background microbial loads of total aerobic mesophilic organisms and anaerobic lactic acid bacteria were all reduced due to UV-C treatments and the yeast and mold populations gradually decreased for all dose treatment groups and fell below the limit of detection after 2 weeks during storage. The firmness of tomato was not affected by the UV-C doses during post treatment storage and also there was no consistent change occurred in tomato color during storage due to UV-C treatments.

From a practical point of view, UV-C treatment is a simple and inexpensive method of processing which leaves no residues behind and may prove worthy for use in post harvest situations to improve safety and to maintain quality of tomatoes. The results of this study indicate that the specific location of pathogens on the produce surface influences the effectiveness of UV-C to achieve specific levels of reduction, which should be taken into consideration for the design of UV-C systems for produce surface sanitation.

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